METHOD AND MICRO POWER GENERATOR FOR GENERATING ELECTRICAL POWER FROM LOW FREQUENCY VIBRATIONAL ENERGY

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. provisional application Serial No. 60/537,821, filed January 21, 2004 and entitled "Electromagnetic Micro Power Generator for Low Frequency Environmental Vibrations by Using Mechanical Frequency Up-Conversion."

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support from the National Science Foundation under Award No. EEC-0096866 . The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to methods and micro power generators for generating electrical power from low frequency vibrational energy.

2. Background Art

The following references are referenced herein:

[1] B. Koenaman et al., "Feasibility of Micro Power Supplies for MEMS," JMEMS, Vol. 6, No. 4, pp. 355-362, Dec. 1997.

[2] M. Mizuno et al, "Investigation of a Resonance Microgenerator," J. OF MICROMECH. MICROENG., Vol 13, pp. 209-216, 2003.

[3] S. Meninger et al. "Vibration-to-electric Energy Conversion," IEEE TRANS. ON VLSI SYSTEMS, Vol. 9, No. 1, pp. 64-76, 2001.

[4] C.B. Williams et al., "Analysis of a Micro-electric Generator for Microsystems," SENS. AND ACTUATORS A, Vol. 52, pp. 8-11, 1996.

[5] C. B. Williams, R.C. Woods, and R.B. Yates, "Feasibility Study of a Vibration Powered Micro-electric Generator," IEEE COLLOQUIUM ON COMPACT POWER SOURCES, pp. 7/1-7/3, May 1996.

[6] R. Amirtharajah, S. Meninger, J.O. Mur-Miranda, A. Chandrakasan, J. Lang, "A Micropower Programmable Dsp Powered Using a MEMS-based Vibration-to-electric Energy Converter," DIGEST OF TECHNICAL PAPERS ISSCC 2000, pp. 362-363, Feb. 2000.

[7] S. Meninger, J.O. Mur-Miranda, R. Amirtharajah, A. Chandrakasan, J. Lang, "Vibration-to-electric Energy Converter," IEEE INTERNATIONAL SYMPOSIUM ON LOW POWER ELECTRONICS AND DESIGN, pp. 48-53, Aug. 1999.

[8] R. Amirtharajah, A. P. Chandrakasan, "Self-powered Signal Processing Using Vibration-based Power Generation," IEEE JOURNAL OF SOLID-STATE CIRCUITS, Vol. 33, No. 5, pp. 687-695, 1998.

[9] R. Amirtharajah, A. P. Chandrakasan, "Self-powered Low Power Signal Processing," IEEE SYMPOSIUM ON VLSI CIRCUITS, pp. 25-26, 1997.

[10] S.G. Kelly, "Fundamentals of Mechanical Vibrations," Chapter 3, McGraw-Hill, 1997.

[11] H. Hosaka et al., "Evaluation of Energy Dissipation Mechanism in Vibrational Microactuators," MEMS '94, pp. 193-198, 1994.

Self-powered remote controlled microsystems are needed in many emerging applications including environmental monitoring and military applications. The required power for these systems can be generated mainly in two ways: 1) by using electrochemical batteries and micro fuel cells; and 2) by energy scavenging from environmental sources such as ambient heat, light, and vibration. Although electrochemical batteries and micro-fuel cells can provide more power, they are not desirable for some applications due to chemicals and reactions involved during the generation process. Also, they have a limited life time.

Energy scavenging from ambient sources has become popular recently, because of its clean power generation process and long life-time.

Among the other environmental energy scavenging sources, vibration is particularly attractive because of its abundance, and several scavenging techniques based on piezoelectric, electrostatic and electromagnetic transduction have been reported [1-9]. The maximum voltage and generated electrical power from a vibrating mass is strongly dependent on the external vibration frequency [4], and drops dramatically at low frequencies (1-10 Hz). But it is at these low frequencies where most ambient vibration exists. Figure 1 shows the maximum power from an electromagnetic generator vs vibration frequency. In Figure 1, it is assumed that the applied external vibration matches the generator resonance frequency. Most reported devices are only capable of operating at frequencies of several kHz; at lower frequencies they are ineffective.

Published U.S. patent application 2004/0007942 discloses an integrated MEMS resonant generator system including a plurality of piezoelectric microgenerators which generate a voltage in response to vibrational energy.

Consequently, there is a need for a method and micro power generator for converting vibrational energy having an ambient, relatively low frequency to electrical power.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a method and micro power generator for generating electrical power from low frequency vibrational energy.

In carrying out the above object and other objects of the present invention, a method for generating electrical power from low frequency, vibrational energy is provided. The method includes receiving vibrational energy having a low frequency. The method further includes converting the low frequency, vibrational energy to vibrational energy having a high frequency greater than the low frequency, and converting the high frequency, vibrational energy to electrical power.

The step of converting the high frequency, vibrational energy may be performed electromagnetically, piezoelectrically or electrostatically.

The low frequency may be in the range of 1 to 100 Hz, or may be in the range of 1 to 10 Hz.

The step of converting the low frequency, vibrational energy may be performed mechanically.

The step of receiving the low frequency, vibrational energy may include the step of providing a micromechanical first resonator device, the first resonator device resonating in response to the received vibrational energy.

The first resonator device may have a mechanical resonance frequency in the range of 1 to 100 Hz.

The step of converting the low frequency, vibrational energy may include the step of providing a micromechanical second resonator device. The

second resonator device may resonate at the high frequency in response to the resonating first resonator device.

The second resonator device may have a mechanical resonance frequency in the range of 1 to 10 kHz.

The second resonator device may include an array of micromechanical resonators.

Further in carrying out the above object and other objects of the present invention, a micro power generator for generating electrical power from low frequency, vibrational energy is provided. The generator includes means for receiving vibrational energy having a low frequency. The generator further includes means for converting the low frequency, vibrational energy to vibrational energy having a high frequency greater than the low frequency, and means for converting the high frequency, vibrational energy to electrical power.

Still further in carrying out the above object and other objects of the present invention, a micro power generator for generating electrical power from low frequency, vibrational energy is provided. The generator includes a micromechanical first resonator device which resonates in response to the vibrational energy. The generator further includes a micromechanical second resonator device, and a circuit coupled to the resonator devices for coupling the resonator devices together so that the second resonator device resonates at a high frequency greater than the low frequency when the first resonator resonates. The circuit also converts the high frequency, vibrational energy to electrical power.

The high frequency, vibrational energy may be converted electromagnetically.

The low frequency may be in the range of 1 to 100 Hz, or may be in the range of 1 to 10 Hz.

The conversion of the low frequency, vibrational energy may be performed mechanically.

The circuit may include a magnet and at least one coil which moves relative to the magnet. Voltage may be induced on the at least one coil by electromagnetic induction.

The first resonator device may have a mechanical resonance frequency in the range of 1 to 100 Hz.

At least one of the magnet and the at least one coil may be mechanically coupled to the devices so that the magnet and the at least one coil move relative to one another to generate voltage on the coil.

The second resonator device may have a mechanical resonance frequency in the range of 1 to 10 kHz.

The second resonator device may include an array of micromechanical resonators wherein each of the resonators has a coil formed thereon.

The above object and other objects, features, and advantages of the present invention are readily apparent from the following detailed description of the best mode for carrying out the invention when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a graph of maximum electrical power versus frequency for an electromagnetic generator operating at different vibration frequencies;

FIGURES 2a-2c are schematic views of a mass mounted on one beam which vibrates at a relatively low frequency which moves another beam to vibrate at a relatively high frequency to realize mechanical frequency up-conversion;

FIGURE 3 is a schematic view of a ball-and-cantilever approach for frequency up-conversion;

FIGURES 4a-4c illustrates the proposed micro-generator structure; Figure 4a is a schematic perspective view, partially broken away, to show a suspended magnet and cantilevers having coils formed thereon; Figure 4b is an enlarged sectional view which shows metal mounted on the distal ends of the cantilevers for actuation by the magnet; Figure 4c is a sectional view of a microgenerator formed on a pair of semiconductor chips which have been joined together;

FIGURE 5 is a graph of force versus cantilever tip movement which illustrates the forces effective on the cantilever movement showing the catch and release points;

FIGURES 6a and 6c are graphs of generated voltage versus time and FIGURES 6b and 6d are graphs of instantaneous power versus time; these graphs illustrate the comparison of emf and generated power values for large mass/coil and frequency up-conversion;

FIGURES 6e and 6f are enlarged portions of the graphs of Figures 6c and 6d, respectively; and

FIGURES 7a-7i are cross-sectional views which illustrate the fabrication process for the micro-generator.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

One of the main ideas for the power generation method and generator presented herein is mechanical frequency up-conversion. This mechanical up-conversion can be done in several different ways. One simple method to implement this is to use two cantilevers across each other as shown in Figure 2 (a). The cantilever on the right has a mass on the tip, and its resonance frequency is adjusted for the target ambient vibration frequency (f_2=1-100Hz). As this cantilever resonates with environmental vibration, at some point of its trajectory it touches or engages the cantilever on the left and forces it to move from its stationery position (Figure 2b). When the right cantilever disengages the left cantilever, the right cantilever continues on with its movement, but at this time the left cantilever starts to resonate at its resonance frequency (f_1), which is designed to be much higher than f_2 (Figure 2c). This happens again and again at each cycle of the right cantilever. For each cycle of the right cantilever, the left cantilever makes f_1/f_2 cycles, and hence mechanical frequency up-conversion is realized. The distance between the two cantilevers and their overlap area during the contact time are important design parameters for its operation.

Figure 3 shows another approach to achieve mechanical frequency up-conversion. In this case a ball (or a cylinder) moves or rolls inside a cabinet with environmental vibration. A set of cantilevers are placed in the same cabinet, and the ball's movement is confined in an area such that it will touch the cantilevers at their tips with a pre-designed overlapping. When there is a contact between the ball and the tip of a cantilever, the cantilever is forced to move from its stationary position. As the ball passes across it, the cantilever starts resonating in its resonance frequency, which is designed as a much higher frequency than the ambient vibration. The beauty of this implementation is that, the ball can move at any ambient vibration. In other words, it is not resonating at one specific ambient frequency which is the case for the system shown in Figures 2a-2c.

Both of these approaches are similar to the operational principle of music boxes where different tunes are created by frequency up-conversion.

Cylindrical music boxes include a wind-up spring, a metal musical "comb" with a number of notes, and a cylinder with projections on it's surface. As the cylinder rotates the projections lift and release a variety of the tuned comb teeth to produce a song. During this process, the wound spring rotates the cylinder with a low frequency f_1, and this frequency is up-converted by means of the projections and the comb teeth.

Another method to realize mechanical frequency transfer is to use a magnet. Due to its simplicity and MEMS compatibility, this is a preferred technique for use in the micro power generator. Figures 4a-4c are various views of the proposed system, which has two resonating devices or structures. The upper resonator structure, generally indicated at 40, includes a diaphragm 41 suspended with a soft spring (*i.e.*, diaphragm beams 42) and has a low resonance frequency that is adjusted for the target application (1-100Hz). It carries a magnet 43 such as an NdFeB permanent magnet 43 for both mechanical frequency up-conversion and electromagnetic power generation. The lower resonator structure, generally indicated at 44, includes a cantilever beam (or array of beams 45 as shown in Figure 4b) which has a higher resonance frequency, and supports one or more coils 46 for electromagnetic power generation, and a magnetic tip 47 that is attracted to the magnet 43 when in close proximity to the magnet 43. As the diaphragm 41 resonates in response to external vibration, it gets closer to the cantilever(s) 45 located beneath it. The distance between them is adjusted such that the magnet 43 catches the cantilever(s) 45 at a certain point of its movement, pulls it (them) up and releases at another point. The released cantilever(s) 45 starts resonating at its/their mechanical resonance frequency which may be set to 1-10 kHz, and hence mechanical frequency conversion is realized.

One of the most important aspects of the design of Figures 4a-4c is the adjustment of magnet catch and release points. The magnetic force generated by the magnet 43 and the mechanical spring force of the cantilever(s) 45 have been modeled using MATLAB. Figure 5 shows these two forces vs. tip movement distance, indicating the catch and release points of the magnet 43. In order to

decrease damping and maximize generated power, the device can be operated in vacuum.

Although this approach reduces the coil size and beam deflection, energy conversion is more efficient than when a similar sized magnet 43 resonates at low frequency above a large area coil (due to higher resonance frequency and speed of the beam). Figures 6a-6f show expected voltage and power generated by a high frequency resonant beam in vacuum compared to a low frequency resonating mass/coil. As these figures show, the generated voltage and power are improved by 10 and 100 times, respectively.

One of the main advantages of the present invention is the mechanical frequency up-conversion by means of the magnet, which can increase the power transfer efficiency. Operating the system in vacuum increases the decay time in generated voltage and power, and hence allows high ratios in mechanical frequency up-conversion. In other words, there is a trade-off between the damping ratio and the mechanical frequency conversion coefficient.

Simulations

As previously mentioned, the overall system has been modeled in MATLAB for calculation of generated voltage, power, catch and release points, and damping coefficient. To provide comparison, a large magnetic mass resonating on top of a single coil is also simulated. Table 1 shows the parameters for the simulation.

TABLE 1
Simulation Parameters

Parameter	*Frequency Up-Conversion*	*Large Mass/Coil*
Resonance Frequency	11.4 kHz	25 Hz
Coil Area	400x300 μm^2	5x5 mm^2
Coil Turns	37	50
Magnet Material	NdFeB (1.1T)	NdFeB (1.1T)
Magnet Size	2x2x1 mm^3	2x2x1 mm^3
Environment	Vacuum	Vacuum

The induced voltage on a coil by means of a vibrating magnet at resonance can be represented as [2]:

$$V_{em} = \frac{B l_p \omega_n Y_0}{2\gamma} \sqrt{1 + 4\gamma^2} \sin(\omega_n t - \Delta)$$

where l_p is the practical coil length (approximately nxl, n: number of coil turns, l: coil length across the magnetic flux), B is the magnetic field, Y_0 is the ambient vibration amplitude, γ is the damping coefficient, Δ is the phase difference, and ω_n is the resonance frequency.

For frequency up-conversion technique the situation is slightly different due to the forced motion of the cantilever. By using the equation of motion for a damped vibrating system with initial condition [10], the electromagnetically induced voltage on the cantilever coil can be expressed as:

$$V_{em} = \frac{l_p B x_0}{\sqrt{1-\gamma^2}} e^{-\gamma\omega_n t} \omega_n \left(\gamma \sin(\omega_d t) + \sqrt{1-\gamma^2} \cos(\omega_d t)\right)$$

where ω_d is the damped resonance frequency and x_0 is the initial displacement (the release point). Note that the voltage has an exponential dependence on time.

Maximum power can be calculated using these equations. As previously mentioned, Figures 6a-6f show the generated power from a low frequency resonating mass/coil and a high frequency resonant beam in vacuum. As the figure shows, maximum power generated by the frequency up-conversion technique is two orders of magnitude larger than the large mass/coil case.

Although the power decreases exponentially in time, the rate of decrease can be controlled by controlling the damping. There are two types of damping for the beams: mechanical and electrical. Mechanical damping is composed of four main components [11] (airflow force, squeeze force, internal friction and support loss), and can be expressed as:

$$\gamma_m = \frac{3\pi\mu b + (3/4)\pi\mu b^2\sqrt{2\rho_a\mu\omega}}{2\rho_b h b^2\omega} + \frac{\eta}{2} + \frac{0.23h^3}{l^3} + \frac{\mu b^2}{2\rho_b g_0^3 h\omega}$$

where ρ_a is the mass density of air, ρ_b is the mass density of the cantilever, μ is viscosity, ω is the vibration frequency, b is the width of the cantilever, l is the cantilever length, h is the thickness of the cantilever, η is the structural damping factor and g_0 is the distance between cantilevers.

Electrical damping depends on inductive coil properties and the electrical load, and can be expressed as:

$$\gamma_e = \frac{(Bl_p)^2}{2\omega_n m R_0}$$

where m is the cantilever mass, ω_n is the resonance frequency, and R_0 is the load resistance. Damping factor decreases considerably in vacuum. Besides

vacuum operation, lower rate frequency up-conversion and larger number of cantilevers help to maximize the average power.

As previously mentioned, one of the most important parts of this design is the adjustment of magnet catch and release points. The catch point is the location of the cantilever at which the magnetic force effective on it is larger than the spring force, i.e.:

$$F_s < F_m, \qquad kx < \frac{B^2 A_m}{8\pi \times 10^{-7}}$$

where k is the spring constant, A_m is the cantilever area for magnetic attraction, and B is the magnetic field expressed as:

$$B = \frac{B_r}{\pi}\left(a\tan\left(\frac{a_1 a_2}{2z\sqrt{a_1^2 + a_2^2 + 4_z^2}} \right) - a\tan\left(\frac{a_1 a_2}{2(z+d)\sqrt{a_1^2 + a_2^2 + 4(z+d)^2}} \right)\right)$$

where a_1, a_2 and d are the magnet dimensions, and z is the distance from the magnet. Figure 5 shows these two forces vs. distance, indicating the catch and release points of the magnet. For this example, the magnet catches and releases the cantilever(s) at around 30 and 100μm distances, respectively.

The micro-generator is preferably fabricated as two separate silicon chips 70 to be combined at the end of the process. These chips 70 and 70′ are fabricated on the same wafer with the identical process flow requiring 5 masks. Figures 7a-7i show the process flow.

First, an oxide layer (71 and 71′) is formed on the silicon substrates 70 and 70′, respectively. This layer (71 and 71′) provides isolation between metal bond pads and the silicon substrates 70 and 70′.

Next, a 5μm-thick parylene layer (72 and 72′) is deposited and patterned at the bonding pad and cantilever areas 80 and 81, respectively (Figure 7a).

Then, coils (*i.e.*, inductors) are formed by sputtering and patterning the first metal layer 73 (Figure 7b).

As the next step, a second 5μm-thick parylene layer (also 72) is formed on the metal and patterned at the contact areas 82 between two metal layers (Figure 7c). This parylene layer 72 provides isolation between the two metal layers.

Then, the second metal layer 74 is formed by using a ferromagnetic material such as nickel (Figure 7d). This metal is used for both magnetic actuation and electrical routing purposes.

After forming the second metal layer, another parylene layer (also 72 and 72′) is deposited to increase the thickness and adjust the resonant frequency of the cantilevers (Figure 7e).

Next, the silicon substrate 70 and 70′ is etched from backside by DRIE to define diaphragm and cantilever areas (Figure 7f).

By etching the sacrificial oxide, the devices are released and the two separate chips are obtained with cantilevers 83 (Figure 7g).

Before combining the two chips, a magnet 75 is placed on top of the parylene diaphragm 72′ of the second chip by means of a micro manipulator (Figure 7h).

Finally, the two chips are combined or joined with a spacer or separator 76 therebetween (Figure 7i). This separator can be made of either silicon or plastic material for precise control of the distance between the two chips.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention.